Renewable and Sustainable Energy Reviews 16 (2012) 4465–4469

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Environmental efficiency evaluation based on data envelopment analysis: A review

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ARTICLE INFO

Article history:
Received 18 September 2011
Received in revised form
23 April 2012
Accepted 28 April 2012
Available online 20 June 2012

Keywords:
Undesirable outputs
Environmental efficiency assessment
Small samples

ABSTRACT

The paper aims to investigate the achievements of the theoretical and practical basis of environmental policy analysis in order to study their works and point out the future possible research direction. It sorts out researches about environmental efficiency assessment and reviews the works about the theory and application of efficiency analysis around the world. It is suggested that environmental efficiency evaluation theory under small samples and DEA method with undesirable outputs will further extend the research on environmental efficiency evaluation. Also, this review confirms that more studies in methods and their applications in this area are in urgent need.

Contents

1. Introduction

Environmental issues have become one of the most important problems related with social and economic sustainable development. Evaluating environmental efficiency in different regions and sectors has strong practical implications. This work not only benefits for people understand the difference among their environmental performances, but also provides an objective reference point for improving environmental performances. However, the current evaluation methods for environmental efficiency are mostly based on the determination of the inputs and outputs evaluation index. Some evaluation methods (such as the data envelopment analysis, Stochastic Frontier Analysis) are proposed based on the macro data or micro data. Finally, the environmental efficiency is measured. Because environmental efficiency evaluations are very complex, the negligence of application scenarios and invariably using some specific traditional evaluation methods may lead to the following disadvantages in practice: (1) failure to take into account environmental efficiency for small samples results in imprecise evaluation; (2) the selection of the variables has a great deal of subjectivity; and (3) some curing and non-dynamic evaluation methods can not deal with the change of socio-economic environment. Solving these problems is important for the development of environmental efficiency evaluation methods.

Now, measuring environment efficiency has become an essential direction in research. So far, scholars have proposed several quantitative models to solve the complex environmental problems [1]. More and more people have generally recognized the importance of environmental efficiency evaluation because it can provide designers and public policy makers with quantitative information for performance evaluation, policy analysis and public

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2012.04.052

communication. All of these benefits will make the decision of environmental policy-making more scientific, empirical and systematic than before.

So far, there have been many quantitative analysis techniques in environmental efficiency evaluation, among which the production efficiency analysis has drawn widespread interests in recent years. Modern production efficiency analysis began to be applied in the study of environmental problems in 1980s, and with more concerns on the environmental problem. The efficiency evaluation method is widely used in environmental evaluation systems [2]. Data envelopment analysis (DEA) is an effective non-parametric method for evaluating the relative effectiveness of the decision making units (DMUs) [3,4]. The exact functional relationship (refer to function formula) between inputs and outputs need not be considered in DEA technology. DEA does not need decision maker to provide the information on weights. The weights can be gained through a programming, that is, no pre-estimated parameters are needed. Therefore, the weights can avoid being subjectivity. But the traditional DEA efficiency model only considers the desirable outputs while neglecting the undesirable outputs in the actual production process. In fact, the undesirable output is usually produced companied with the desirable outputs. For example, in a thermal power plant, it is inevitable that undesirable outputs will be generated in the power generation process, such as the emissions of carbon dioxide. The output maximization assumption of the traditional DEA efficiency model can not be applied for this scenario. Therefore, how to consider the undesirable outputs in the traditional DEA efficiency model becomes a topic with great theoretical significance and application value. To deal with this issue, many scholars have worked on the environmental efficiency and gained a lot of achievements [5–11]. Concluding the current works and pointing out some interesting and valuable directions for measuring the environmental efficiency are urged, so this review is believed to be necessary and timely.

The rest of this paper is structured as follows. Section 2 reviews major related researches. Section 3 introduces the DEA models with undesirable output and classifies them into several parts. Finally, concluding remarks are given in Section 4.

2. Origin of environmental efficiency evaluation

Comprehensive evaluation on the environmental efficiency traces to the time when researchers focused on the limited energy and the carbon dioxide emissions generated in the production. By simulating the carbon dioxide emissions scenario, early researchers provided some advice for energy policy in the future. Edmonds and Reilly thought that the establishment of a global energy environment evaluation model is very important for energy analysis and environmental decision-making, and they proposed the global energy and economic development model which can predict changes for the next one hundred years [12]. Additionally, they gave the specific structure of the model and explained the results of this model. By analyzing the quantitative relationship between the global natural gas distribution and carbon dioxide, Reister proposed that the main determinant of carbon dioxide emissions was the energy supplier, so the key to controlling carbon dioxide emissions is to control its source [13]. Harvey believed that the increase of carbon dioxide concentration would promote the effects of photosynthesis. Based on this, he developed a formula to analyze the impact that the carbon dioxide volume fraction on the carbon preservation parameters of photosynthesis, and further studied the global carbon cycle model through simulating carbon dioxide fertilization effect [14]. Gustavsson et al. indicated the government can establish efficient energy end-use technologies, cogeneration and a recycling economy through the implementation of policies. The energy system can still reduce carbon dioxide emissions by 75% through end-use technologies, cogeneration and circular economy without increasing water and power consumption under sustaining economic growth [15]. Kamiuto built a simple model including the air, the biosphere and the hydrosphere to describe the global carbon cycle, and he found that since the chaos deforestation and the changes in land use around 1875, the original "big tank" which absorbed carbon dioxide has reduced or disappeared, thus changing the carbon dioxide emission rate [16]. Svendsen took Denmark as an example and proposed that carbon trading should be introduced into plants in the private sector, and management department of the public power sector should be built, in order to reduce carbon dioxide emissions by 25% by 2005; Meanwhile, the carbon tax would reach US$50 per family, the transportation sector and private plants were not included at that time [17]. Yang and Zhang introduced five approaches of calculation methods of carbon dioxide emission from bio-energy utilization, which were summarized from the perspective of resources and utilization [18]. However, most of the above works are qualitative. The quantitative evaluation for environment system with multiple inputs and outputs is badly needed as the impact factors on carbon dioxide emissions compose a complex system.

Soon after, some researchers have begun to pay attention to reducing greenhouse gas emissions, and have presented some multi-objective decision analysis models and Integrated Assessment of Climate Protection Strategies (ICLIPS) evaluation methods. Färe et al. introduced environmental efficiency variables based on the decomposition of total factor productivity in the pollution variables and input–output efficiency variables, and formed the environmental efficiency variables, giving the calculation methods as well [7]. Diesendorf built models considering ethical principles, target groups, evaluation and implementation strategy, in which all levels of government, business and community organizations in collaborative efforts are involved. He indicated that the most important thing is to speed up community participation and empowerment in order to form a better atmosphere to promote the implementation of sustainable development policies and coordination of environmental protection and socio-economic development [19]. Zaim and Taskin established the environmental benefits variables using a non-parametric method for each OECD member country, and measured the output they sacrificed to achieve better environmental benefits [20]. Voorspools et al. investigated several types of possible indirect sources of greenhouse gases, and used life cycle assessment to measure two different types [21]. Their empirical results suggested that nuclear power produces minimal greenhouse gas emissions, followed by wind power in coastal areas, and the worst among the three was photovoltaic power. Matthews designed an evaluation method for bio-fuel production systems of energy and carbon budget [22]. He thought that further research should validate the input assumptions and evaluate the integrity and utility of the budget, as well as the energy generation systems. Sands and Leimbach also proposed core methods for Integrated Assessment of Climate Protection Strategies (ICLIPS), in which they use agriculture and land-use models, using the carbon emissions evaluation program where the land use changes were the main cause for the overall greenhouse gas emissions [23]. In their simulation, land-use changes significantly affected carbon emissions. Pasurka calculated the changes in nitrogen oxides and sulfur dioxide emissions with the inputs changes of technology, fuel and non-fuel by using the new decomposition model and the distance function. Besides, he suggested that the major emissions of sulfur dioxide decreased with the changes of output groups, while nitrogen oxides decreased along with the fuel consumption

and the changes of output groups [24]. Manan et al. introduced a framework for the implementation of a Malaysian energy efficiency award, which is proposed based on the survey conducted in their research, and on various models of energy award implementation around the world [25]. Although these studies have promoted the optimization for environmental policies in a certain degree in a number of countries and regions, researchers have also come to realize that the sustainability of energy conservation and environmental protection is largely interactive with the efficiency increase in the production process, which means that the economic efficiency with environmental considerations need to be studied [1].

The impact factors of environmental efficiency include the total profit of resources consumption, its total investment, profits, the amount of resources, the ratio of GDP to energy consumption, environmental performance and resource production. Apart from that, technology, utility, supply, demand, and staff and resource availability are also important factors in the constraints of environmental efficiency. Meanwhile, as for the objective evaluation of environmental efficiency, we must also consider the most important factor—the availability of sample data, and avoid the query of the reliability of the quantitative evaluation for environmental efficiency. Because there are few studies on environmental efficiency analysis and DEA is a very powerful tool to measure the efficiency, this paper will focus on the DEA efficiency models considering undesirable outputs and the analysis on these environmental models. In the following sections, we will review the efficiency analysis theory and its applications, and explore the achievements of these results to provide theoretical foundation and objective basis for environmental policy analysis and design as well as its possible deficiencies.

3. DEA model considering undesirable outputs

As one of the main tools of the production process efficiency analysis, the DEA technique has drawn more and more researchers' attention since it was proposed by Charnes et al. [26]. Now it has received great developments over the past thirty years [26,27]. Many researches focus on its applications or its theory developments, especially theoretical aspect. Many DEA methods are proposed, such as the models of efficiency measure, imposition of restrictions on the weight method, investigation of variable characteristics and modeling aspects of data transformation, etc. Environmental efficiency as an interesting topic has both theoretical value and practical meaning. So far the researchers have achieved a great deal of achievements in both aspects of environmental efficiency evaluation.

During the production process under normal circumstances, undesirable outputs will be inevitably produced, such as a variety of environmental pollutants. This situation can not meet the "maximum outputs" hypothesis of traditional DEA efficiency model, so undesirable outputs must be specially treated to expand traditional DEA efficiency model [28]. Taking undesirable outputs into the technical efficiency evaluation framework, we must minimize resource inputs while reducing emissions of undesirable outputs under the circumstance of keeping the product output unchanged, or maintain the same input target while increasing the desirable outputs and reducing undesirable outputs as much as possible.

DEA efficiency models considering undesirable outputs can be divided into three categories. The first category is taking the undesirable outputs as inputs for processing [29,30], but it can not reflect the real production process in some degree [11]. The second category is conducting data transformation to undesirable outputs first, and then evaluating the environmental efficiency by using the traditional efficiency model based on the transformed data [11,31]. Due to strong convexity constraints, it can only be solved under variable returns to scale. The third category is considering the disposability of production technology into non-parametric DEA model, which is produced by Färe et al. [5,6,9,32], and then further extended by more studies [33–36]. Meanwhile, Rovere et al. suggested that a new approach is urgently needed to takes into account the technical, socioeconomic, environmental and technological factors of the various alternatives for sector expansion at the same time. They also indicated that multi-criteria analysis may be a good evaluation tool [37]. Although practical value of this approach is verified, this approach only drew a few scholars' attention [38].

Among many measures methods, the most common one for evaluating the efficiency is the radial efficiency measure, which is reciprocal to the Shephard's distance function. More generalized distance function also is formed in DEA models based on the traditional Shephard's distance function [39]. Besides the above two, the hyperbolic efficiency measure can increase the desirable outputs and reduce undesirable outputs [5]. The non-radial and slack-variables-based efficiency measure considering undesirable outputs in the non-parametric DEA efficiency model framework bring a new flavor to this problem [40,41].

With the international community's focus on the environment and sustainable development issues, it is very necessary to integrate the environmental factors into the study of production efficiency. The non-parameter DEA model has been widely applied in environmental efficiency assessment research because DEA does not need a functional form of the production frontier before evaluation and has great flexibility. Moreover, this method provides the measure for improving the performance of decision making units [2]. Färe et al. first deals with pollution variables by using weak disposability of the inputs and outputs. Weak disposability assumes the change of undesirable outputs definitely affects the other outputs, that is, if you want to reduce pollution and other undesirable outputs, some desirable outputs must be given up as a result [5].

Since Färe et al. proposed the first DEA model to deal with undesirable outputs with the weak disposability, the environmental efficiency evaluation considering the undesirable outputs were largely extended [5]. Allen, Sarki and Talluri had summarized the applications of the DEA model in environmental efficiency research [42,43]. Lansink and Reinhard took pollutants as input variables and explored the technical efficiency and potential technology growth of Dutch pig farms based on weak-treatment DEA model [44]. Li and Cheng suggested dealing with desirable and undesirable outputs simultaneously in the DEA model, and built a new DEA model for analyzing forty-six city industrial sectors productivity of China [45]. Kordrostami and Amirteimoori proposed the environmental efficiency evaluation of decision-making units with chain internal structure, and provided a corresponding efficiency evaluation index based on the multi-component efficiency evaluation method [46]. Murty et al. estimated environmental efficiency; Malmquist produced an index and a shadow price of pollutants of the Indian sugar industry, based on Weak and Strong Disposability of Bad Outputs [47]. Brannlund et al. and Gomes and Lins also developed a carbon emissions quota model based on the non-expected output and non-parametric DEA efficiency model [48,49]; Zhou et al. proposed carbon emissions decomposition analysis method based on the environmental DEA technique and Shephard's distance function [34]. Researchers have developed a variety of DEA efficiency models considering undesirable outputs, including environmental performance evaluation, environmental regulation impact assessment, pollutant emission quota, shadow prices of pollutants estimation and other environmental systems assessment problems. Some results are also related to the following aspects:

The first method is taking undesirable outputs as investments [30,50–52]. Environmental pollutants and other undesirable outputs are often associated with resources invested in the production process, increased and reduced with desirable outputs, which has similar relationship with the traditional production function between inputs and outputs. In the efficiency evaluation process, deal with undesirable outputs as an input indicator added to the DEA model, and take this model to analyze the environmental efficiency of decision making units. Haynes et al. proposed an environmental protection production frontier to research the environmental efficiency based on data envelopment [52]. Reinhard et al. analyzed the environmental efficiency of Dutch dairy farms with DEA, and compare with the random production frontier evaluation methods [53]. Hailu and Veeman analyzed the environmental efficiency of the Canadian paper industry using DEA methods [30].

Second one is data transfer function method [11,28,54]. The data transfer function method considers the pollutants as outputs, and at the same time, transfers the-smaller-the-better undesirable outputs into the-bigger-the-better desirable output, and then takes the transformed output as an ordinary output, analyzing environmental efficiency of decision making units with the traditional DEA model. There are three data transfer function forms: the negative output method, the linear data transfer method [11] and the non-linear data transfer method [28,54].

Third one is distance function method. Chung took pollutants into the technical efficiency analysis framework and proposed a DEA Environmental Efficiency model based on distance function and weak handling of pollutants by which a especially direction is set [39]; when the efficiency of the decision making unit is improved along the direction, one can increase desirable outputs while reducing undesirable outputs properly. By this method, the defect of the above two methods, i.e., a one-dimensional change, can be made up, such as not reflecting the production process, undermining the convex of production possibility set, etc. This method breaks through the traditional method of radial measure of efficiency improvement and has certain superiority.

4. Conclusions

In this paper, we review the current studies on the environmental efficiency evaluation. The background why this problem draws more and more researchers' attention is introduced in details. More importantly, the route of this direction is firstly illustrated. Then more works are focused on the non-parametric DEA technique with undesirable output because this approach has a lot of advantages on evaluating the environmental efficiency. Now, many achievements have done on this area.

However, the non-parametric DEA efficiency model is essentially a non-random technique. Traditional DEA has some deficiencies. For example, it does not consider the uncertainty of the data, it can not make statistical inferences for the efficiency analysis results, and it does not give an obvious statistical significance of the evaluation value.

Studies that consider statistical properties of undesirable outputs of the non-parametric DEA efficiency model are rare, and achievement of environmental efficiency evaluation based on small samples is even more rare [55]. All these factors mean that there are many statistical defects both in considering undesirable outputs DEA method itself and improving analysis of the environmental efficiency quantitative evaluation under small samples conditions [56,57]. Therefore, the following aspects of conducting research will further promote the depth and breadth of considering non-expected output environmental efficiency evaluation method:

Research on evaluation theory and method based on small samples. How to improve the evaluation accuracy of environmental efficiency under small sample condition is an issue to be addressed. Under the circumstances of small overall sample size or unknown distribution error term of traditional modeling methods, the statistical inference only based on original sample data is not credible; when using the evaluation system model based on these, the evaluation precision is not satisfying. So we must take full account of defects from the perspective of information disclosure on environmental protection, analyze the characteristics of environmental efficiency evaluation under small samples circumstances, and establish environmental efficiency evaluation models by using a new method, namely applying V-fold and Bootstrap. It is also needed to determine the optimal value of V, and to test the effectiveness of parameter t value hypothesis of small samples based on the Bootstrap method.

Research on environmental efficiency evaluation theory and method based on undesirable outputs DEA. In order to achieve a more accurate quantitative evaluation of environmental efficiency, we need to establish a series of new DEA models based on studying specific characters of environmental efficiency evaluation, including: the efficiency measure type aspect, using a series of non-radial DEA models to study undesirable outputs of environmental efficiency evaluation different from the traditional approach; building two-goal DEA model of environmental efficiency, taking into account the desirable outputs increasing and undesirable outputs reducing in the model, and solving the model. On the basis of these studies, non-radial-two-goal DEA environmental efficiency model will be presented considering undesirable outputs, and these models will be solved by appropriate methods and techniques, so we can get closer to the actual evaluation results of environmental efficiency. Then, by putting random factors into the common non-parametric-efficiency DEA model considering undesirable outputs, analyzing the influence of environmental efficiency evaluation results by these random factors and statistical noise is then possible.

Research on environmental efficiency evaluation method and its applications on the condition of small samples. When current environment-related data is of insufficient disclosure, the characters of environmental efficiency evaluation system is similar to the characters of small sample modeling method combined with the DEA model considered undesirable outputs. This requires a proper combination of small sample optimization and DEA model considering undesirable output. The evaluation model and evaluation system should be established and then corresponding application should be carried out in order to guide the future environmental efficiency evaluation.

Acknowledgments

We would like to thank the supporting of National Natural Science Foundation of China (71171001, 70901069), National Social Science Fund Project of China (10BGL066), Humanity and Social Science Youth Foundation of Ministry of Education of China (10YJC630208), Key Foundation of Natural Science for Colleges and Universities in Anhui, China (KJ2011A001), and Key Foundation of National research in Statistics of China (2011LZ023).

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